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Fiber vs. Copper in the Last 500 ft

Abstract: In this white paper we compare and contrast both the practical and fundamental differences between optical fiber (fiber) and a range of copper-based transmission media: unshielded single twisted pair (STP), Category 5e cable (Cat5e), and coaxial cable (coax). The context for the comparison is a canonical 500 ft final drop to a customer's premise in an access network. It will be demonstrated that in order to provide truly competitive converged or triple play services (defined herein) STP must be augmented with an additional access line, either Cat5e or coax, whereas fiber supports all known services over a single media. In addition, today's demonstrated or planned capacities of STP, Cat5e, and coax are all near to the fundamental limits, whereas only fiber offers effectively unlimited potential for expanding capacity to support tomorrow's unforeseen bandwidth hungry applications. Finally, a range of operational considerations are addressed comparing each access media.

Introduction

A side-by-side comparison of optical fiber and copper wires based on fundamental capacity is a topic well studied and reported in an endless list of references. It is clear today that the bandwidth capacity of optical fiber is several orders of magnitude greater than copper wires according to any metric considered. However this question has been recently revisited based on very short distance applications, as for example in access networks, where there are competitive architectures that use either fiber or copper for the last 500 ft connection to the end user. The simple question is: are fiber and copper equivalent for distances less than or equal to 500 ft?

It is well known that the bandwidth capacity of any lossy medium decreases with increasing distance, and vice-versa. Capacity or bandwidth capability grows very rapidly as total distance is shortened and this is the rationale behind the question posed above.

Since this behavior is true for both copper and fiber, it is natural that the fiber capacity differential is maintained even for short distances, since fiber attenuation is radically lower than copper. This fact alone fundamentally negates the presumption of equivalence between fiber and copper for any distances, including those shorter than 500 ft.

While fiber and copper are certainly not capability-equivalent in principle, this might only be an academic distinction considered from a practical application perspective. In particular, for links shorter than 500 ft it might be that copper supplies all the capacity needed to support today's applications and those in the foreseeable future. We will see below that STP, even in the most aggressive VDSL scenario, cannot match the capabilities of fiber to deliver the full suite of services offered today.

In order to these issues, we will present in the following sections some analyses of typical and ultimate performance for different copper and fiber transmission media and compare these performance levels with current and future service requirements.

Finally we will present some additional considerations to complete a comparison of optical fiber and copper based on a broader suite of attributes other than bandwidth alone.

Fundamental Limits of Fiber and Copper

It is widely understood and acknowledged that optical fiber has nearly limitless information carrying capacity relative to either STP or coax cables, and that coax in-turn has greater capacity than STP. To quantify these statements an excellent place to start is the spectral attenuation curves of each media.

For STP the attenuation scales as the square root of frequency[1], with the following explicit functional relationship:

$$\text{Attn [dB/km]} = 0.02\times\sqrt{\text{Freq [Hz]}}$$

[1] Integrated Circuits for Data Transmission Over Twisted-Pair Channels *by David A. Johns and Daniel Essig*: IEEE Journal of Solid-State Circuits, Vol. 32, No.3, March 1997.

Similarly, coax cables also have a square root dependence of attenuation with frequency[2]. For typical coax deployed in access networks, the overall attenuation is approximately a factor of six lower than for typical STP. This is represented by decreasing the factor of 0.02 in the above equation by a factor of six. However, because of the square root dependency, the total bandwidth capacity of coax is $6^2 = 36\times$ larger than for STP.

Category 5e cable[3] contains four twisted pairs, carefully designed to minimize crosstalk between pairs, reduce other degradations, and to increase guaranteed available bandwidth. However, from a pure attenuation perspective, each pair in a Cat5e cable has the same spectral attenuation characteristics as a STP. Therefore, the maximum capacity that can be provided by a Cat5e cable is nominally

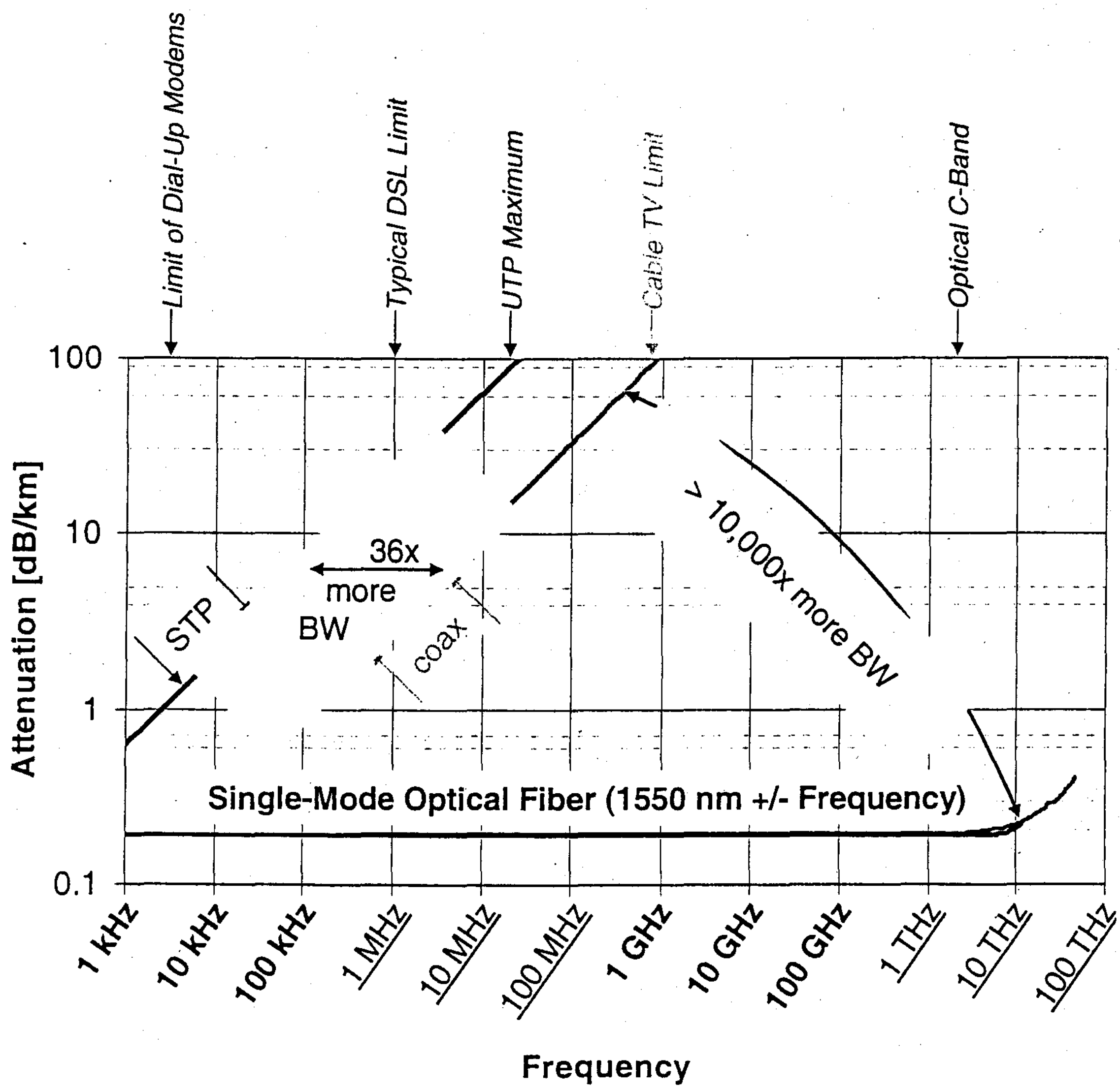

Figure 1: Spectral attenuation curves for STP, coax, and fiber.

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[2] See the standard text Classical Electrodynamics, Second Edition *by J.D. Jackson*: John Wiley & Sons 1975. Coax attenuation data available at http://www.timesmicrowave.com/cgi-bin/calculate.pl.

[3] Category 5e cable is defined in the ANSI/TIA/EIA-568-B.x group of standards. B.1 is the umbrella "Commercial Building Telecommunications Cabling Standard", and B.2 is the copper specific "100 Ohm Twisted Pair Cabling Standard".

four times larger than for a single STP.

However, in standard telco cables containing multiple STPs, near-end cross-talk (NEXT) and far-end cross-talk (FEXT) between different pairs will limit the capacity of individual STPs in the cable to less than ¼ the max capacity of a Cat5e cable.

Taking into account the full impact of NEXT and FEXT the maximum downstream and upstream capacities of DSL over STP in realistic cables can be computed for a range of reaches[4]. The maximum is based on an optimum sharing of the bandwidth to minimize impairments between DSL signals in adjacent STPs in a single cable. For 500 ft it is found that the maximum downstream traffic is 150 Mb/s and the maximum upstream traffic is 50 Mb/s.

For comparison, the 1000BASE-T Gigabit Ethernet standard[5] for transmission over Cat5e cable specifies a full duplex, *i.e.*, bi-directional, reach of 100 meters. Scaling the results of Song et al[4] to 100 meters and multiplying by 4 gives an estimate that four DSL lines over four STPs can provide 650 Mb/s downstream and 210 Mb/s upstream, which is indeed less than the capabilities of Cat5e cable.

As previously stated the intrinsic bandwidth capacity of coax cables is 36 times greater than for STP based solely on attenuation. This means that over 500 feet we would expect that coax could provide downstream capacities in excess of 5 Gb/s[6]. Another way to understand this is that coax cables can support up to 156 analog video channels[7]. Digitized using 256 QAM[8], each 6 MHz analog channel provides 38 Mb/s capacity. This product (134×38 Mb/s) is greater than 5 Gb/s.

The intrinsic capacity increase of optical fiber relative to copper can be demonstrated in multiple ways. First of all, Figure 1 shows the spectral attenuation curves for STP, coax, and single-mode optical fiber. To place these curves meaningfully on the same chart it is necessary to use logarithmic scales for both axes. Additionally, STP and coax both have minimum attenuations at zero frequency, but optical fiber has its minimum attenuation at approximately 194 THz (an optical wavelength of about 1550 nm). Therefore, it was necessary to plot the optical fiber spectral attenuation curve as a function of frequency relative to 1550 nm. Unlike the STP and coax curves which are positive frequency only by definition, the optical fiber curve will have two branches. These are both displayed, but on the scale of the chart are practically indistinguishable. The optical fiber attenuation data plotted in Figure 1 is estimated from 1250 nm to 1650 nm.

In Figure 1, the 36× frequency shift of the coax curve relative to the STP curve is readily apparent. The optical fiber attenuation curve is so much lower and broader than the STP and coax curves that it is difficult to fully appreciate the increase in intrinsic bandwidth provided by fiber. For instance, as the optical fiber attenuation is less than 0.2 dB/km, the loss over 500 ft and over a multi-THz window is about 0.03 dB, which is typically less than the connectors at either end of the fiber, and so irrelevant.

From the perspective of Ethernet, the latest 10 Gigabit Ethernet standard[9] is primarily a fiber-only specification, although a copper interface amendment has been discussed. In any case, this illustrates the inevitability of fiber over copper as services and demand grows.

Some other data points to illustrate the enormous capacity of optical fiber:

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[4] Dynamic Spectrum Management for Next-Generation DSL Systems *by K.B. Song, S.T. Chung, G. Ginis, and J.M. Cioffi*: IEEE Communications Magazine, October 2002.
[5] GigE: IEEE 802.3ab
[6] 36×150 Mb/s = 5.4 Gb/s
[7] National Cable Telecommunications Association (NCTA)/EIA
[8] QAM = Quadrature Amplitude Modulation. As 256 QAM contains 8 bits ($256 = 2^8$) per symbol, a 6 MHz channel can nominally support up to 48 Mb/s. In practice, the standard data throughput is 38 Mb/s. See DOCSIS 2.0 standard.

[9] 10 GigE: IEEE 802.3ae

- In excess of 10 Tb/s transmission results have been achieved over 100+ kilometers of optical fiber[10].
- Estimates of ultimate capacity in excess of 100 Tb/s[11][12].
- Commercially announced products[13] offer capacities exceeding 1 Tb/s over thousands of kilometers.

BANDWIDTH AND SERVICES

Television-quality video transmission is widely acknowledged as the most bandwidth-hungry of consumer applications. There are several potential ways of transmitting video signals over STP, and an overly simplistic comparison of bandwidth requirements for each technique without a clear description of the differences between them can lead to misleading conclusions.

We describe four methods of transmitting video over STP. 1) Broadcast analog, 2) Broadcast standard definition digital, 3) Switched Digital Video (SDV), and 4) Switched high-definition TV (HDTV). The first option of broadcast analog transmission, which requires 6 MHz of continuous bandwidth per channel, is the overwhelming majority transmission technique in use today. Although, in principle, sufficient bandwidth is available to support 2 to 3 analog channels over 500 ft of STP only one of the three VDSL potential standards[14][15][16] allows for greater than 6 MHz of continuous bandwidth. Therefore, analog video distribution is not universally supported over STP in VDSL architectures. The broadcast digital option digitizes and compresses the original analog signals to potentially allow for propagation of the standard offering 78 distinct channels. As each digitized channel requires about 4 Mb/s[17] For television quality, the simultaneous propagation of 78 channels would require more than about 320 Mb/s as represented on Figure 2.

The third option of switched digital video deviates significantly from the broadcast technique that has defined the television experience for consumers for nearly 60 years. Effectively, only a few (typically 3 or fewer) channels are transmitted to a user simultaneously. As a consumer "changes the channel", signals are transmitted to the network operator's central location (a "headend", or "central office"), to indicate that new "stream" must be sent. This technique causes the user to experience some service latency, but does allow for an approximation of multichannel video to be supported over a bandwidth-limited infrastructure. Since the average household in the US has about 3 televisions[18], we assume for Figure 2 that at least three channels have to be transmitted simultaneously. Using the same 4 to 5 Mb/s requirement as before for digital video, we get a total bandwidth of about 12 to 15 Mb/s necessary for this video system transmission.

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[10] In particular NEC labs at OFC 2001 in post-deadline session 24 presented an experiment showing 10.92 Tb/s capacity transmitted over 117 km of optical fiber.

[11] Nonlinear limits to the information capacity of optical fiber communications *by Partha P. Mitra & Jason B. Stark*: Nature, Vol 411, June 2001, 1027-1030.

[12] Ultimate Spectral Efficiency Limits in DWDM Systems *by Joseph M. Kahn & Keang-Po Ho*: OptoElectronics and Communications Conference, Yokohama, Japan, July 8-12, 2002.

[13] Alcatel's 1626 Light Manager 192-Channel Long Haul and Ultra Long Haul DWDM System provides 1.92 Tb/s of capacity.

[14] ANSI T1.424/Trial Use Part 1 contains two 4 MHz downstream spectral blocks.

[15] ITU G.993.1 Amendment 1 similarly contains two 4 MHz downstream spectral blocks.

[16] ETSI TS 101 270-1 v1.2.1 contains a single 10 MHz downstream spectral block.

[17] The Motion Pictures Expert Group has developed a series of standards maintained by ISO/IEC. The dominant video digitization and compression standard is MPEG-2 (ISO/IEC 13818 family). For TV quality DVD, the target is 3.5 Mb/s, but 4-5 Mb/s is commonly used. We will use 4 Mb/s.

[18] US Census Bureau, 2002 Statistical Abstract of the United States

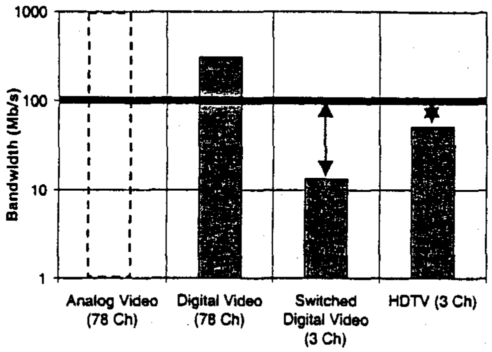

Figure 2: Video Options over STP

The last video transmission system represented in the chart on Figure 2 is the HDTV technology, requiring 19.4 Mb/s per channel. Again using the previous assumptions, the chart shows a bandwidth requirement of nearly 60 Mb/s, and that limit is possible only with the limitation of a switched architecture.

There are a range of VDSL standards under discussion, as we have seen, with a range of downstream capacities available. For the medium range of the systems, about 10 Mb/s, none of the accepted video delivery techniques can be supported over an STP infrastructure. For the most aggressive VDSL standards, up to 52 Mb/s, only the switched digital video option is available. Finally, even the theoretical maximum of 150 Mb/s will not support today's standard 78 channel broadcast video.

However, two factors should be noted: 1) a switched digital video service is not equivalent to broadcast video from a user experience perspective due to latency and the limitations on "channel surfing", and 2) the bandwidth requirement for these services (either regular digital transmission or HDTV) represents a significant portion of the overall STP transmission capacity, dramatically reducing the bandwidth available for data transmission.

In light of the preceding discussion, it becomes difficult to see how an STP infrastructure can simultaneously offer next-generation access services (viz. high speed always-on data) and converged services which are truly competitive with the overwhelmingly accepted and preferred delivery mechanisms. The addition of a coax infrastructure to support the aggressive requirements of video delivery could indeed complement twisted pair, but this leads to an obvious practical dilemma when compared to optical fiber, in light of the fundamental limitations inherent in all copper media, as detailed earlier. STP obviously requires a network operator to undertake deployment and installation of a complementary copper medium, viz. coax, to truly support advanced services. In light of this, why should a network provider not opt instead for a more robust and capable optical fiber installation to gain a single infrastructure with radically expanded capabilities? From both fundamental as well as obvious practical considerations, the choice clearly becomes fiber.

Additional Considerations

Beyond both the inherent fundamental and practical superiority of optical fiber bandwidth capability compared to that of copper, whether it be STP or coaxial cable, an optical fiber infrastructure offers significant advantages to both carriers and service customers (both residential and commercial). At the simplest level, an outside plant infrastructure comprising a conductive medium such as copper is inherently prone to a host of undesirable characteristics. Corrosion and deterioration is a significant limitation that is commonly but begrudgingly accepted in the telecommunications world, requiring not only regular maintenance but also cyclical wholesale replacement of the infrastructure to maintain acceptable operating characteristics. With a dielectric medium such as optical fiber, essentially a glass that is not reactive with normal environmental components (air, water, etc.), the infrastructure lifetime is considerably longer than that of copper and requires significantly less maintenance. Beyond that, no evidence has yet to be presented that fiber requires replacement at fixed intervals, as its operating characteristics are remarkably stable over time. For a network operator, the robustness and reliability of a fiber infrastructure allows more appropriate distribution of service personnel along with customer services with higher quality and reduced disruptions.

In a fiber-based passive access infrastructure, active electronic and optical elements are located only at the ends of the network. An all-copper infrastructure typically requires at least several repeaters/amplifiers to accommodate its inherently high signal loss, and the extreme case of a hybrid copper and fiber deployment requires more intelligent active electronics in the field where the fiber loop terminates at the copper drop location. With field-deployment of actives come the obvious requirements of powering, maintaining, and securing those devices. For telco-grade service capabilities, both always-on power and backup powering are mandatory for a copper infrastructure, requiring appropriate connections and placement, as well as the significant space requirements for full power battery backup systems. In a passive fiber infrastructure, the lack of active electronics in the field allows for smaller and less obtrusive enclosures and more flexibility in deployment location without geographical limitations of power availability. By locating device powering and backup at the customer location, the number of points of failure that can affect multiple customers are dramatically reduced; i.e., the failure of optical conversion equipment in a passive fiber network affects only one customer, whereas failure of such a device in a hybrid copper and deep fiber network will affect all customers served by that device, typically 7-12. From a network operator's perspective, the absence of high power active electronics in a fiber infrastructure also allows for a safer work environment for field technicians, who must otherwise carefully adhere to appropriate safeguards when maintaining and repairing copper-based lines and their associated components, which can often be located in water-soaked or difficult to access areas.

From a signal quality and security standpoint, fiber also has a marked advantage over copper. Signal leakage and interference issues that plague both coaxial cable and twisted pair copper are effectively non-existent in optical fiber installations, allowing for very high quality voice, data, and video signals. For a network operator, this can ease the cost and complexity associated with regulatory compliance to monitor both signal quality and a system's effects on other unrelated services. For the consumer, this again allows for much higher quality of service and reduced disruptions.

Conclusions

A fundamental comparison of conventional optical fiber with "state of the art" copper media easily demonstrates fiber's technical superiority. Whereas copper is nearing its fundamental limit of information carrying capability, and applications already exist which strain even the experimental and unproven limits of which have been suggested by some, the fundamental limit of optical fiber's capability is nearly unfathomable in the context of residential services. Beyond the clarity in fundamental comparisons, optical fiber also allows for a true shift in operational capabilities, translating into benefits for both network operators and consumers. With ample room for current and emerging technologies, as well as advantages for improved signal quality and security, optical fiber clearly represents the logical and immediate next step from legacy copper access infrastructures.